Communication Networks Academic Research Center: Quality of Information-Aware Networks for Tactical Applications

Tom La Porta –Director

Greg Cirincione, US-ARL Lead

Penn State – Prime

General Members

City University of New York

University of California, Davis

University of California, Santa Cruz

University of Southern California

Sub-Awardees

BBN

University of California, Riverside

Stanford

North Carolina State

The Network Science Collaborative Technology Alliance (CTA)

A Flagship Program for US-ARL and CERDEC

Perform foundational, cross-cutting research on network science leading to:

- A fundamental understanding of the interplay and common underlying science among social/cognitive, information, and communications networks
- Determination of how processes and parameters in one network affect and are affected by those in other networks
- Prediction and control of the individual and composite behavior of these complex interacting networks

Resulting in:

- Optimized human performance in network-enabled warfare
- Greatly enhanced speed and precision for complex military operations

$~160M for 10 years

Network Science CTA

Interdisciplinary Research Center (IRC) – led by BBN

- Ensure research directions of the three ARCs is focused on fundamental network science issues that are military relevant and achievable; perform basic research

Information Networks Academic Research Center (INARC) - UIUC

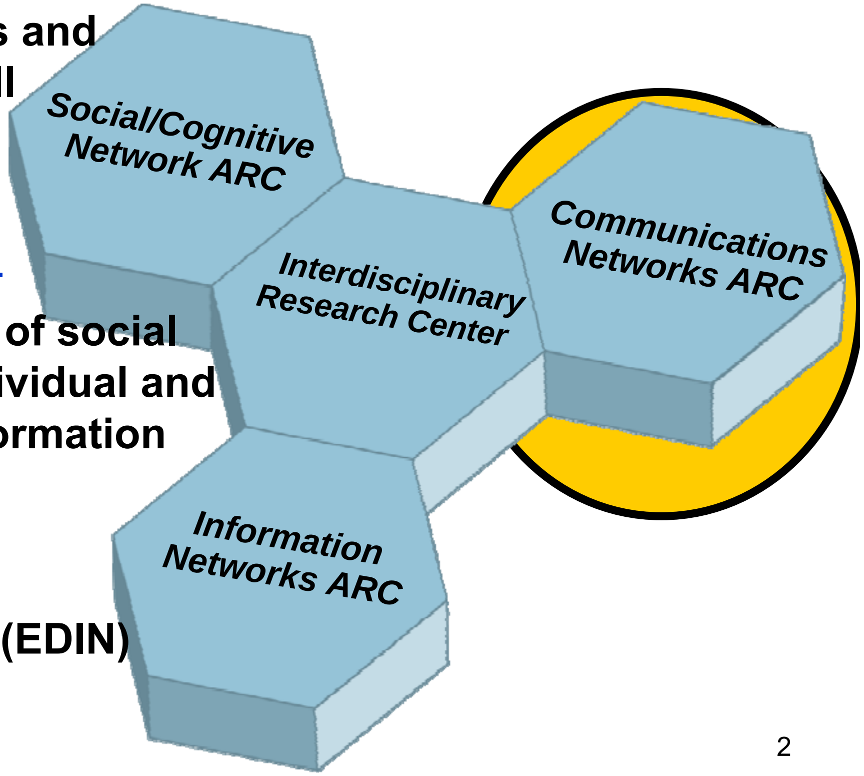
- To develop theories, experiments, measurements and metrics, and ultimately predictive models that will anticipate the behavior of information networks

Social and Cognitive Networks ARC (CNARC) - RPI

- To develop theory, measures and understanding of social and cognitive networks as applicable to both individual and organizational decision making of networked information systems

Two cross-cutting research thrusts

- Evolution and Dynamics of Integrated Networks (EDIN)
- TRUST in a decision making environments



CNARC Vision

Develop foundational techniques to model, analyze, predict and control the behavior of secure tactical communication networks as an enabler for information and command-and-control networks

Network is an <u>information source</u>

– Understand and optimize *operational information content capacity*

Approach

– Understand information needs (context, purpose)

– Understand impact of network on information

Science

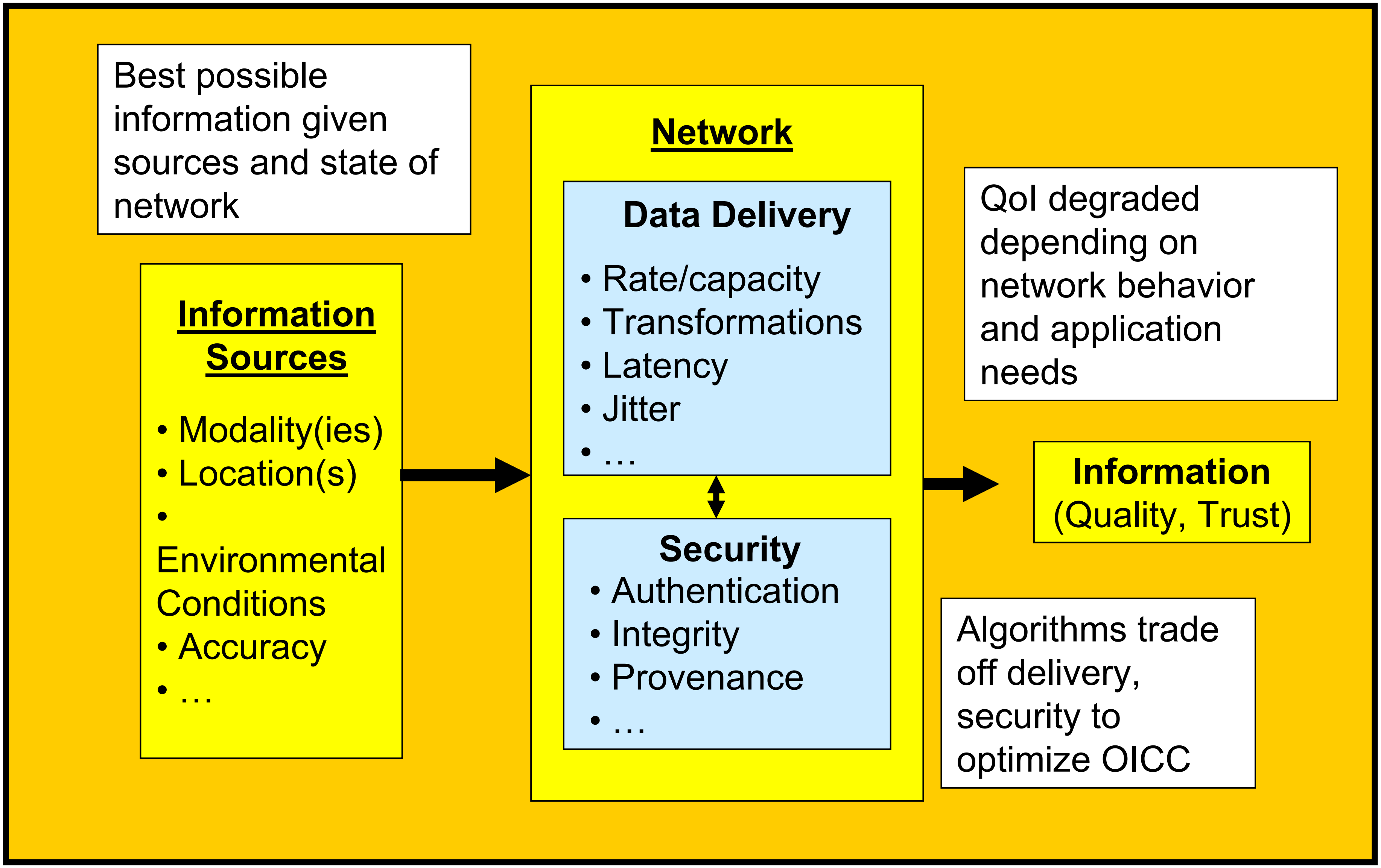
– Characterize network data delivery in terms of impact on information

– Characterize security properties in terms of impact on information

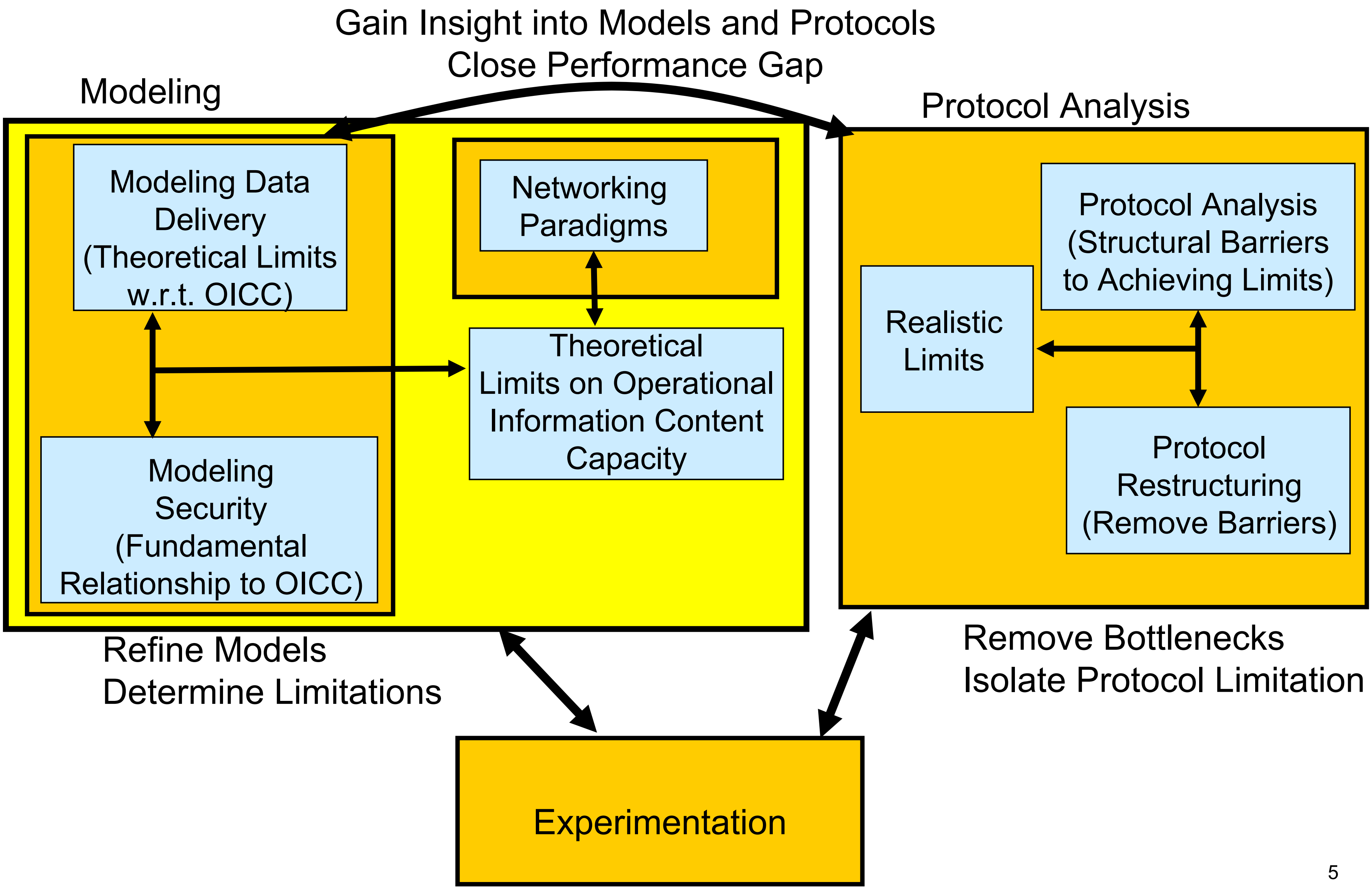
– Develop models that jointly consider overall network impact on information

$35M for 10 years

Overall View of Information Flow



Overview of CNARC Work



CNARC Projects

C1: Modeling and Optimizing Operational Information Content Capacity (Govindan, USC)

C1.1 Characterizing and Optimizing QoI

- Lead: Govindan (USC)
- Bar-Noy (CUNY), Krishmamurthy (UCR), Neely (USC), La Porta (PSU)

C1.2 Modeling and Operational Information Content Capacity and Factors that Impact OICC

- Lead: Yener (PSU)
- La Porta (PSU), Ramanathan (BBN), Psounis (USC), Brass (CUNY)

C1.3 Market-Based Approaches for QoI Aware Networking Using Virtual Currencies

- Lead: Bar-Noy (CUNY)
- Goel (Stanford), Krishnamachari (USC)

C2: Networking Paradigms to Increase OICC (Cao, PSU)

C2.1 In-Network Storage: Characterizing the Benefits of Cooperative Caching

- Lead: G. Cao (PSU)
- Krishnmachari (USC), La Porta (PSU)

C2.2 Increasing the OICC of Disruption Tolerant Networks (DTN) Using Social and Information Links

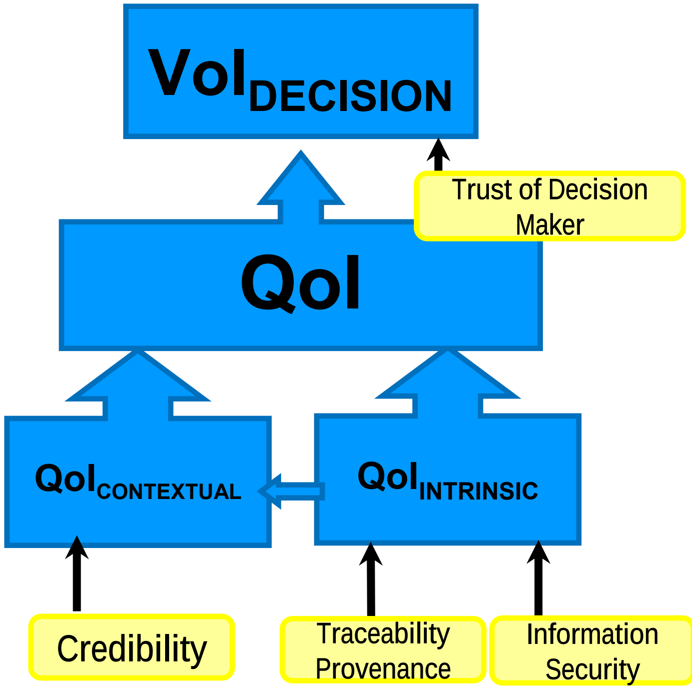
- Lead: J.J. Garcia-Luna-Aceves (UCSC)
- G. Cao (PSU), Psounis (USC)

C2.3 Universal Scheduling

- Lead: Neely (USC)
- Krishnamahari (USC), Yener (PSU), La Porta (PSU)

Task C1.1: Characterizing and Optimizing Quality of Information (QoI) (USC, CUNY, UCR, PSU)

NETWORK SCIENCE CTA



Key Technical Innovations

- Modeling and composing intrinsic QoI functions for several types of information and QoI attributes in forms that can lead to optimization of information quality
- Characterizing QoI as a stochastic measure on the network that considers complex attributes (i.e. information provenance) in the context of network performance

Key Objectives:

- Develop a multi-dimensional stochastic definition of QoI that captures trade-offs in terms of select intrinsic and contextual QoI attributes
- Formulate and solve optimization of QoI in terms of intrinsic and contextual QoI attributes (such as information credibility)

Deliverables:

Q1: Characterization of impact of provenance on QoI

Q2: Impact of corroboration on QoI

Q4: QoI function for video in terms of accuracy, completeness, precision and timeliness (contextual)

Q4: Stochastic optimization framework for QoI

Impact:

Will enable networks to adapt to maximize the information delivered to users based on the quality of information and the context of the decision

QoI Parameters from DoD

	Metric	**General Definition**	**Image**	**Video**	**Text**
$\mathbf{QoI}_{\mathbf{instrinsic}}$	Correctness	Closeness to ground truth	Field of view, resolution		Truthfulness of report
	Freshness	Age	Capture time		
	Precision	Extent of detail	Resolution	Resolution Frame rate	Detail of description
	Security	Protection of information and source	Provenance, authentication, integrity, non-repudiation, confidentiality		
$\mathbf{QoI}_{\mathbf{contextual}}$	Accuracy	Specificity relative to need	Resolution, field of view	Resolution, frame rate, field of view	Ability of reporter
	Timeliness	Availability	Delivery latency		
	Completeness	Total relevance to ground truth	Field of view	Field of view, frame rate	Breadth of description
	Credibility	Extent believable	Trust in information		

QoI Examples

To match a photo with a database of faces (match identity): 1 information bit (yes/no) per image of sufficient QoI

- Intrinsic metrics of interest: precision (bits/pixel), freshness (age of photo)
- Contextual metric of interest: completeness (field of view)
- Network metrics of interest: timeliness (latency), accuracy (bit errors)

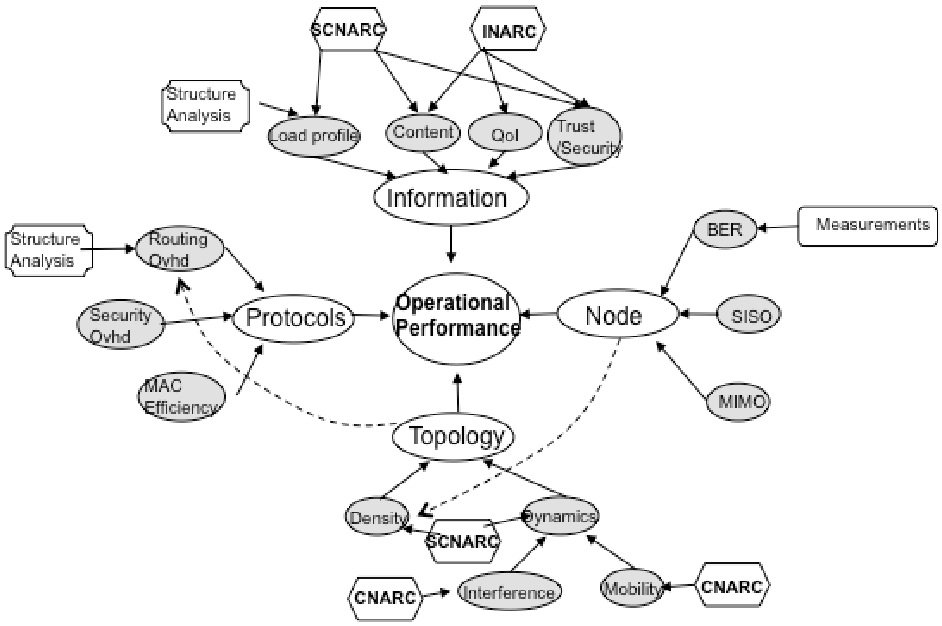
Tradeoffs

- Compression will improve timeliness, but reduce precision
  - Perhaps lowering the 1 info bit/image
- Cropping an image may or may not reduce QoI (contextual)

QoI as a utility function

- Apply optimization techniques
  - Very difficult because on properties of such functions
- Sensitivity analysis needed

Task C1.2: Modeling Operational Information Content Capacity (OICC) and Factors that Impact OICC (PSU, USC, CUNY, BBN)



Key Objectives:

- Define/compute OICC in terms of information types/QoI
- Identify the fundamental limits of the OICC of realistic network tactical networks

Deliverables:

Q1: Symptotic expressions for capacity in grid networks with power law traffic

Q2: Computation of OICC for small networks

Q3: Transformation of symptotic rates to OICC

Q4: Joint OICC-QoI model

Impact:

Modeling the network as an information source that directly supports the information needs of users will provide design insights for maximizing relevant information delivered network-wide

Key Technical Innovations

- A new construct and computational methodology of OICC that considers types of information, capacity, and Quality of Information (QoI) metrics (i.e. security, latency)
- Symptotic analysis of OICC in realistic networks (protocol models, topologies, realistic sizes) to characterize the impact and sensitivity of network parameters on OICC

Example

Goal: match a photo to a person in a database via an image within 1 second

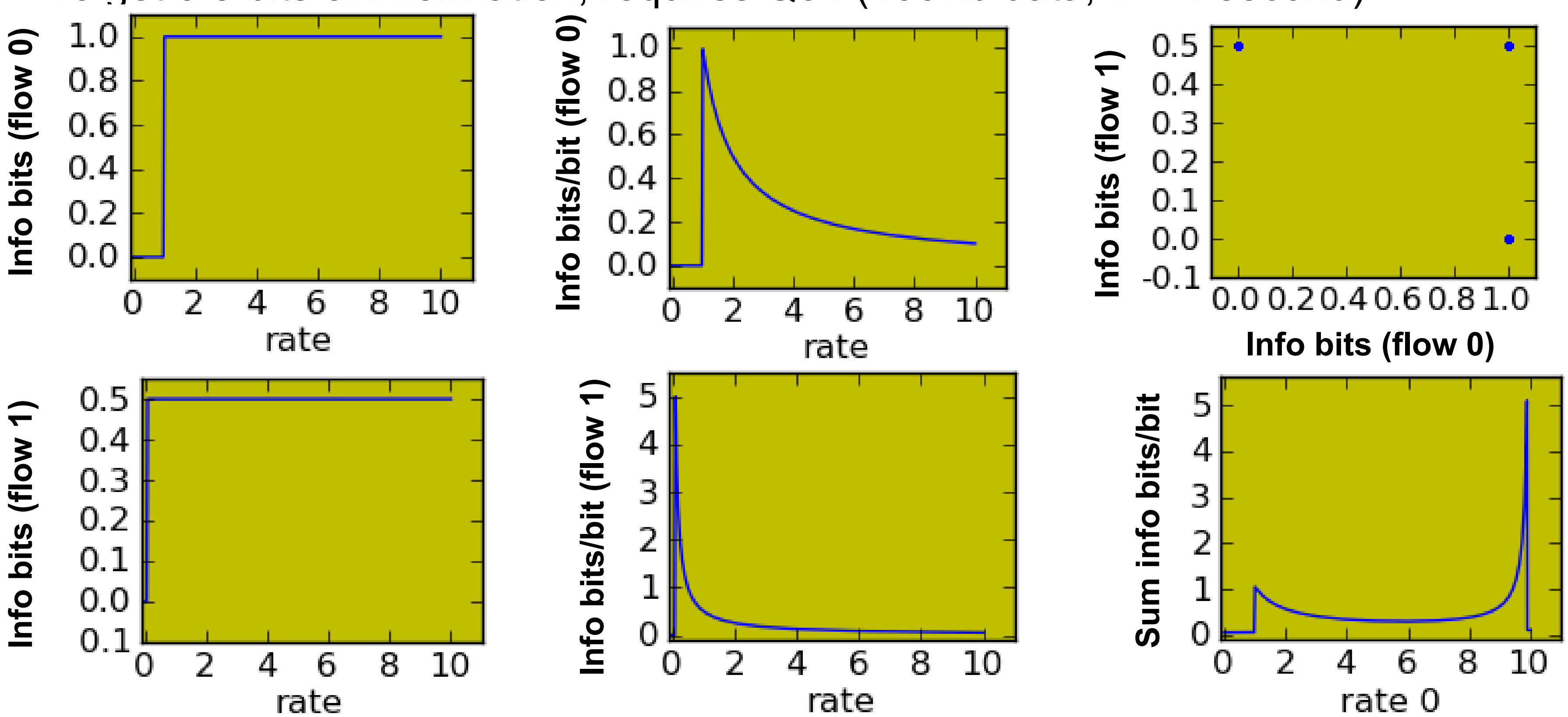
Network supports 10 Mbps perfectly shared by two flows

QoI specification 0

– To get 1 bit of information, requires QoI: (1Mb data, T < 1 second)

QoI specification 1

–To get 0.5 bits of information, requires QoI: (100Kb data, T < 1 second)



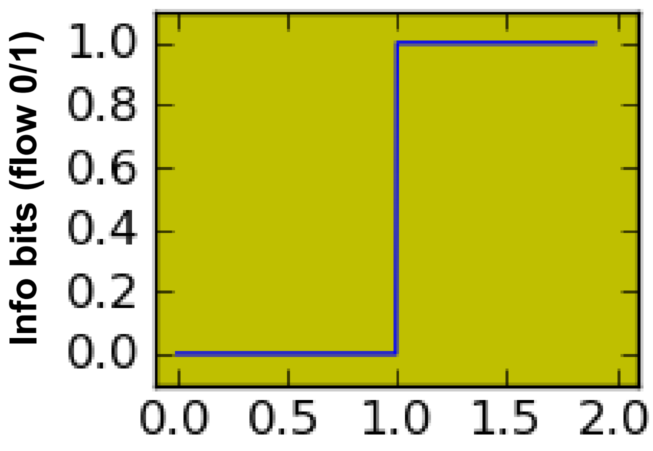
Example 2

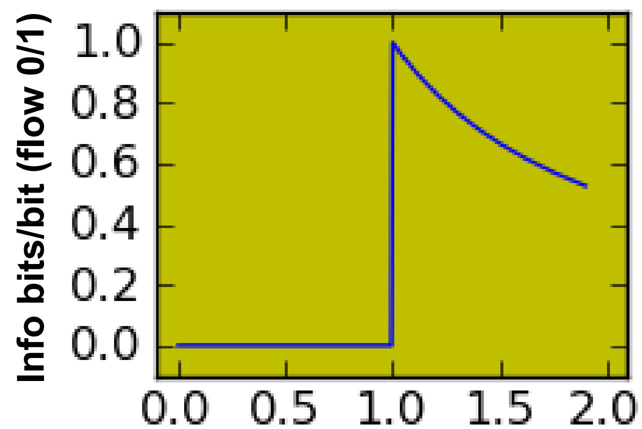
Goal: match a photo to a person in a database via an image within 1 second

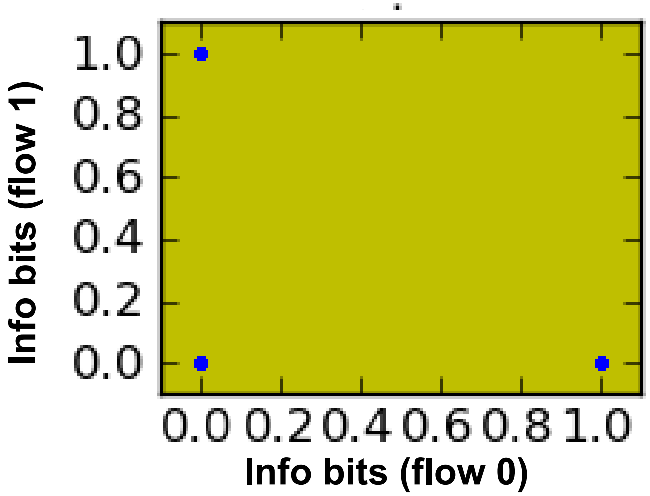
Network supports 1.9 Mbps perfectly shared by two flows

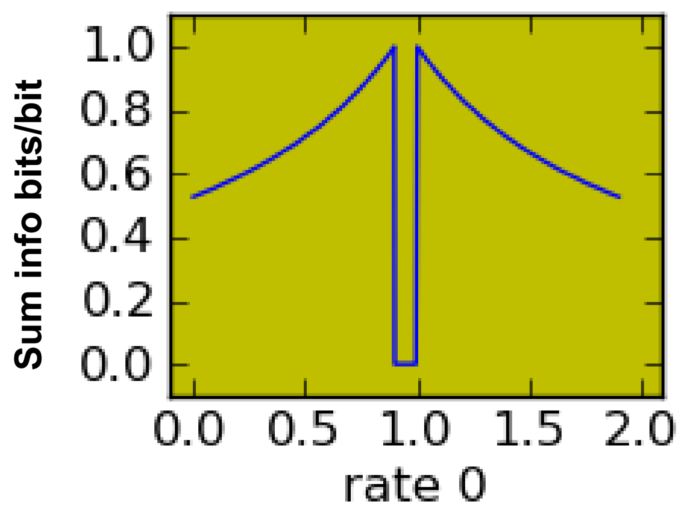
QoI specification 0 and 1

– To get 1 bit of information, requires QoI: (1Mb data, T < 1 second)









Realistic Scaling: Asymptotic vs Symptotic

Asymptotic scalability

– Order of growth of some "metric" (e.g. capacity) as a function of some "parameter" (e.g. number of nodes)

– Unqualified verb: "*Network X does not scale with increasing size*"

– *Does not say at what size it actually fails, only says some such size exists*

Symptotic or "real world" scalability

– Operational performance with a real world, non-asymptotic view, constants and lower order terms not ignored

– Given a network with certain parameters, the number of nodes beyond which adequate performance cannot be achieved

– Qualified verb: "*Network with parameter values {P} scales to 450 nodes*"

– Consider specific topologies, flows, protocols and radio capabilities and the meaning of "adequate performance"

led by Ram Ramanathan of BBN

Motivation: Real-world questions

To how many nodes does my network scale?

- What is the meaning of such “non asymptotic scalability”

Can you give me an equation governing *my* network’s behavior?

- different topology “classes” (line, grid, clustered etc)
- different information exchanges (not just uniform)
- different radio parameters?
- *Incorporating the effect of social and information network considerations*

Which parameters should I try and change to increase my scalability?

- Which ones give me most bang for buck, which ones are a waste of time
- Sensitivity or “change impact” analysis

Gupta-Kumar says MANETs are not scalable. Should I stop funding all research in MANETs?

- Or features that don’t result in O(1) transport capacity (e.g. beamforming)?

Symptotic Scalability

Residual capacity (must be > 0)

Effective capacity (higher the better)

Effective load (lower the better)

$$R = A - U$$

Components of A:

- Data rate, number of relays, number of radios, frequencies, spatial reuse etc.

Components of U:

- Traffic distribution, Routing overhead, MAC/link overhead, etc.

$R = A - \psi - (1 + \Upsilon^j)\, \Sigma_j\, U^j$

- For each component *j* (overhead, traffic, etc)
- Υ^j = contention factor, proportional to neighbor size
- Ψ = fixed factor capacity loss

Symptotic scalability = *n* iff R(n) > 0, and R(>n) <= 0

Transforming Symptotics into OICC

$R = A - \psi - (1 + \Upsilon)\ \Sigma_j\ \zeta X/\alpha$, $X/\alpha = QFR(q_j)$

X is the offered rate of *information* bits

α is the bits of information per bit of data

- **Challenges:**
  - Rationalizing units – bits of information with data bits
  - Determining α
  - Handling non-binary information

- **Symptotic scaling (for a line network)**

$$N \approx \frac{r}{\frac{3QRF(q_j)d}{1-e} + 5Q}$$

N = number of nodes, r = rate of network, d = duty cycle, e = error rate, Q= routing overhead

Scalability and Impact

Instantiating for a line network:

r(ate)=2 Mbps, d(uty cycle)=100%, e(rror rate)=0.05 and Q=260B every 5 seconds

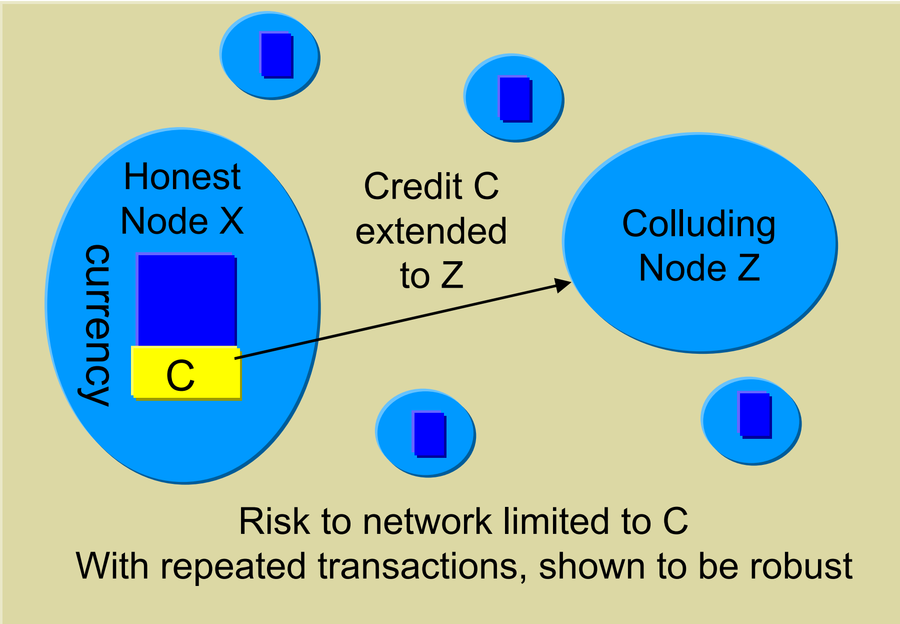
$$QRF(q) = \begin{cases} 10 \text{ kbps for } P \leq 24 \text{ Mpixel} \\ 20 \text{ Kbps for } 24 < P \leq 48 \text{ Mpixel} \\ 30 \text{ Kbps for } P > 48 \text{ Mpixel} \end{cases}$$

If P = 20 Mpixel, network can support 59 nodes

If P = 25 Mpixel, network can support 21nodes

$$N \approx \frac{r}{\frac{3QRF(q_j)d}{1-e} + 5Q}$$

Task C1.3: Market-Based Approaches for QoI-ware Network Using Virtual Currencies (CUNY, USC)



Key Technical Innovations

- Consideration of resource sharing in tactical networks as a market environment (joint with IRC)
- Maximizing QoI within a budget of shared discrete resources (joint with SCNARC)
- Maximization of QoI with continuous optimization of fine-grained resources
- Application of credit networks to bound risks of resource sharing (joint with IRC)

Key Objectives:

- Develop models of market environments for tactical networks to enable efficient market-based solutions to apply
- Characterize benefits of market-based solutions in different shared environments

Deliverables:

Q1: Formulation of virtual currency framework for OICC optimization

Q2: Characterization of credit network properties with respect to QoI

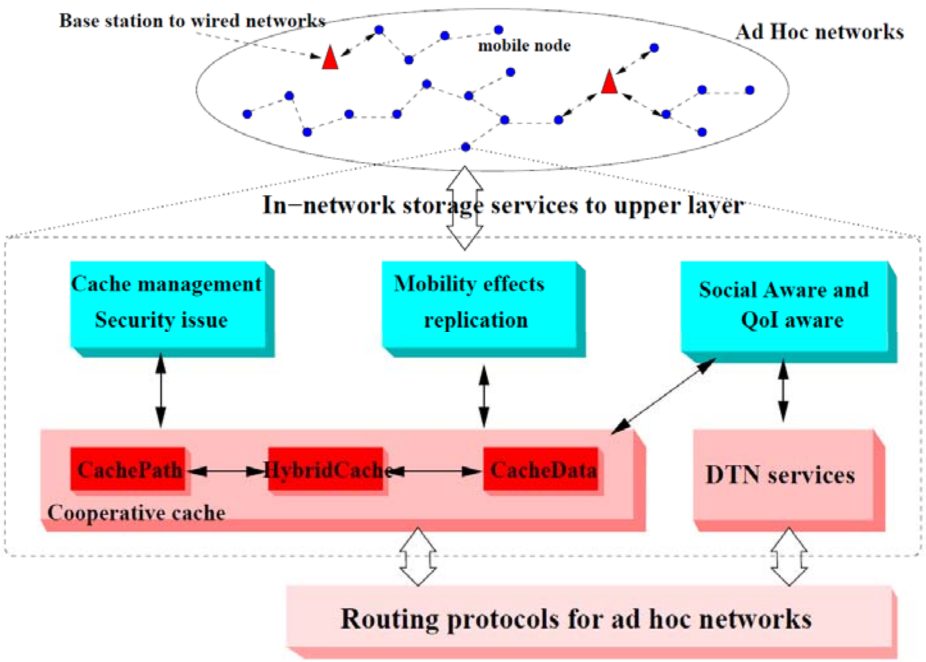
Q3: Consider selfish users in a market and determine existence of Nash equilibrium

Q4: Formal analysis of parameter space for credit networks

Impact:

Enables rich set of market based tools to be commonly applied across all genre of network

Task C2.1: In-Network Storage: Characterizing the Benefits of QoI-Aware Cooperative Caching (PSU, USC)



Key Technical Innovations

- Cache management (information replacement and admission) based on QoI metrics (timeliness, availability, freshness, accuracy)
- Impact of mobility on caching strategies and performance
- Explicit consideration of information links (joint with INARC) and social relationships to drive cache management
- Evaluation on mobile phone platforms

Key Objectives:

- Increase OICC by reducing bandwidth requirements and increasing QoI by making cache management more efficient and QoI-aware
- Understand impact of information links on cooperative caching performance

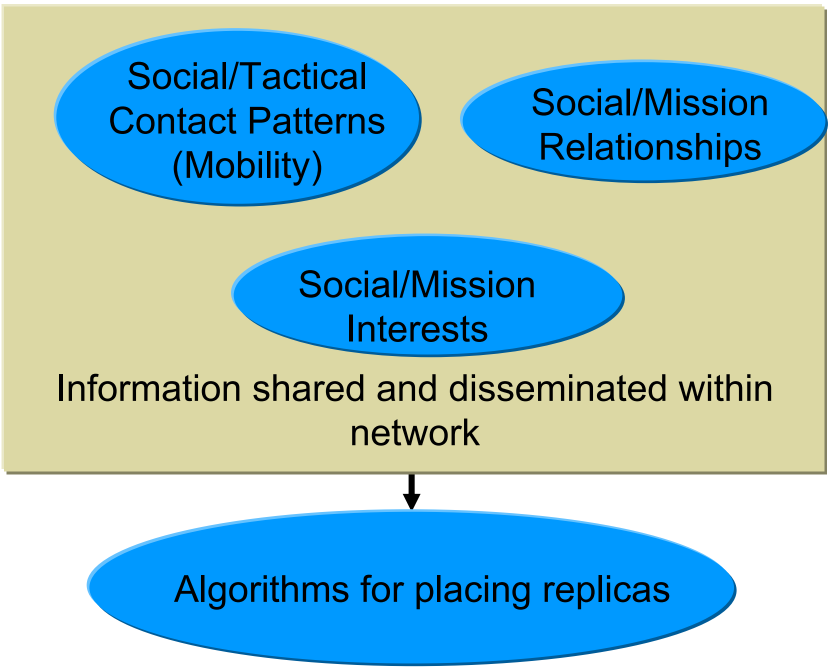
Deliverables:

Q1: Characterize impact of mobility on caching performance
Q2: Characterize QoI tradeoffs for cache management
Q3: Performance bounds of cache performance considering communities of interest
Q4: Obtain performance bounds on cooperative caching considering QoI-aware algorithms

Impact:

- Knowledge of underlying information network, mobility characteristics, and QoI requirements will provide 50%- 200% gains in operational information content capacity

Task C2.2: Increasing the OICC of Disruption Tolerant Networks (DTNs) Using Social and Information Links (PSU, USC, UCSC)



Key Technical Innovations

- Use of contact patterns (not statistics), interests (jointly with INARC) and relationships to locate replicas for data delivery
- Explicit consideration of overhead required to disseminate information amongst nodes
- Introduction of contextual database and low-overhead techniques for updating information
- Validation using tactical mobility traces generated by EDIN

Key Objectives:

- Develop replica placement strategies that are highly efficient to improve the OICC of a network by leveraging knowledge of node and information relationships
- Determine strategies and tradeoffs for sharing information to enable replica replacement algorithms

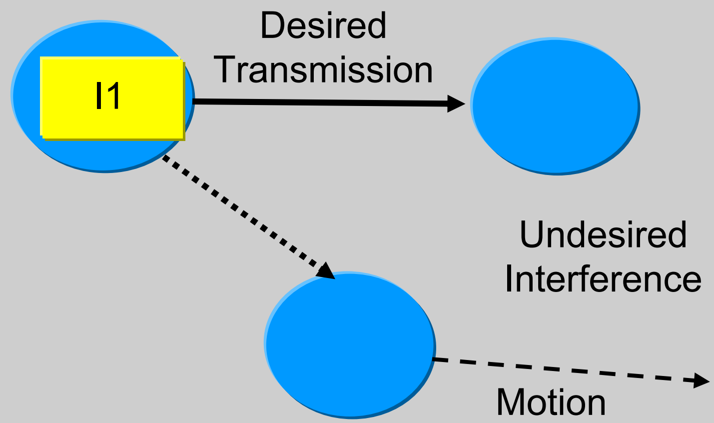
Deliverables:

Q2: Characterize impact of contact patterns on replica placement
Q3: Define control plane of DTN for dissemination of social and information links
Q4: Characterize impact of node relationships
Q4: Determine bounds on the benefits of DTNs given storage bounds and knowledge of social/information links

Impact:

- Improve OICC of a tactical network by better using node storage and mobility to deliver the best information to decision makers

Task C2.3: Universal Scheduling (PSU, USC)



Decision: transmit I1 now with freshness F1 and cause loss, or transmit later with freshness F2 with no loss?

Key Technical Innovations

- Develop a “universal scheduling” theory for QoI that provably learns efficient decisions without knowing the future
- Apply utility maximization and Lyapunov optimization techniques to tactical mobile networks
- Integrate place-holder bit theory and LIFO scheduling into backpressure algorithms

Key Objectives:

- Develop scheduling algorithms that are provably robust to time-varying traffic, channel, and mobility processes considering QoI
- Apply several theories to scheduling framework to optimize OICC in realizable manner

Deliverables:

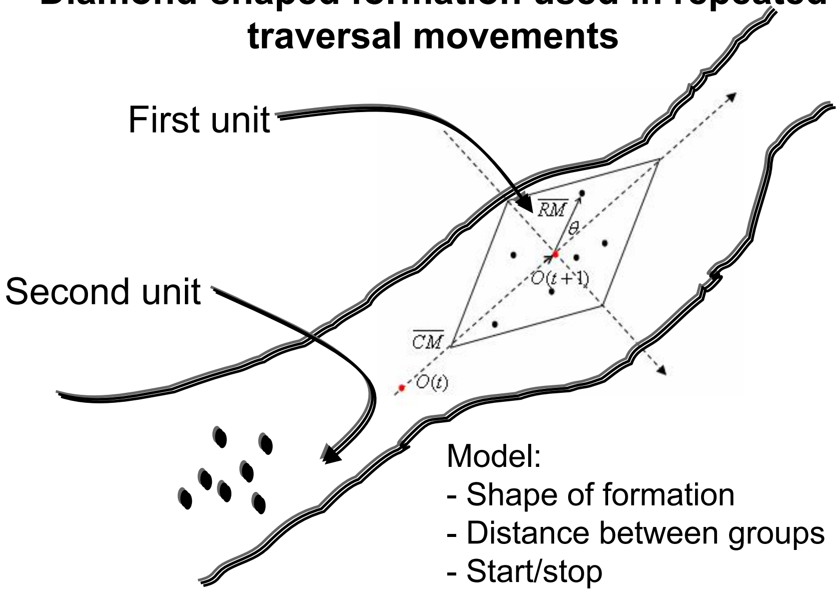
Q1: Contingency-based scheduling algorithm
Q2: Characterize history-based QoI
Q3: Characterize impact of limited information of tactical networks (e.g., mobility model) on universal scheduling
Q4: Integrate LIFO scheduling with mobility to improve OICC

Impact:

Provides a theory of scheduling in networks that is robust in terms of events, traffic, and QoI metrics

EDIN: Modeling Tactical Mobility (PSU, USC, CUNY, BBN)

Diamond-shaped formation used in repeated traversal movements



Model:
- Shape of formation
- Distance between groups
- Start/stop

Key Technical Innovations

- Generation of traces of tactical military movements in varying environments (presence of enemy, availability of resources, terrain)
- Overlay of information objects to track movements and evolution of information needs with mobility
- Reduction of traces into tractable mathematical form to allow accurate analysis of network evolution and impact on algorithms

Key Objectives:

- Develop models statistically equivalent to military movements
- Generate realistic traces which may be used throughout NS-CTA for evaluation

Deliverables:

Q1: Initial hidden Markov Models of generated scenarios

Q2: Traces of pincer movement and repeated traversal under several scenarios

Q3: Initial parameterized models including information overlays

Q4: Validation of models against further traces

Impact:

- Mathematical models for realistic military mobility patterns available for insight into key metrics driving network evolution

Summary

NS-CTA program ongoing

– collaborative efforts starting between all centers

Research Challenges

– integration and co-evolution of multiple genres of network